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Stability of fiber Bragg grating wavelength calibration references

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Abstract: We discuss the key considerations necessary to create stable fiber Bragg grating wavelength references. We describe two high-accuracy measurements to characterize the gratings, and we demonstrate gratings with wavelength stability better than 1 pm over 75 days.

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1. Introduction

For many applications, wavelength reference standards based on molecular absorption lines such as hydrogen cyanide and acetylene are ideally suited. These molecular absorption lines have been characterized with expanded uncertainty (2σ) as small as $\pm$ 0.1 pm [1]. However, some high-wavelength-accuracy applications are not compatible with absorption-line references. For example, there are some wavelength regions for which there are no appropriate molecular absorption lines. Also, the calibration of fiber-optic sensor interrogation units often requires a wavelength reference based on a narrow reflection spectrum rather than an absorption line. High-accuracy calibration is crucial for fiber-optic strain sensors, because wavelength measurement errors as small as 1 pm are equivalent to an error of 1microstrain.

A few years ago, we administered a round robin in which ten different companies were asked to measure the same temperature-stabilized, athermally-packaged fiber Bragg gratings (FBGs) [2]. They sent their measured reflection spectra back to NIST, and we calculated the center wavelengths from the raw data. Comparing the center wavelengths of all the measurements, we found that the results varied by as much as 35 pm, which indicated that there was a serious problem, either in the accuracy of the measurement systems used in the round robin or in the long-term stability of athermally-packaged FBGs, or both.

In this paper, we discuss the development of a stable wavelength reference based on FBGs. There are many factors that influence the measured stability of the artifact, including package stability, errors introduced by the measurement system and the center wavelength calculation routine, and intrinsic FBG characteristics such as reflection spectral shape. We have also developed two high-accuracy measurement systems to characterize our FBGs. We have demonstrated a wavelength reference composed of four FBGs with wavelength stability (2σ) better than 1.0 pm.

2. Designing a stable FBG wavelength reference

2.1 FBG Characteristics

The FBG's spectral properties such as spectral shape, bandwidth, and peak reflectance are important to the design of a stable wavelength reference. For accurate identification of the spectrum's peak wavelength, we need a narrow reflection spectrum, with a clearly distinguishable peak, and we want to avoid gratings with reflection spectra that have flat tops, extreme asymmetries, or large side lobes. We use FBGs with bandwidths of approximately 100 pm, as a compromise between a narrow spectrum for easy peak identification, and a wide spectrum for signal-to-noise ratio (SNR) considerations. Although extremely narrow features (and presumably higher accuracy in peak wavelength identification) can be achieved using a π-phase shift in the grating to create a narrow feature in the reflection band [3], we did not pursue that option, because we wanted FBG spectra that are readily compatible with most FBG sensor interrogation systems.

High reflectance is desirable to achieve high SNR, but gratings with high reflectance tend to develop flat-topped spectra where the peak wavelength is difficult to identify. We modeled the reflection spectra as a function of peak reflectance using a fixed-length, uniform grating model and then fitted fourth-order polynomials to our modeled spectra to predict the effect on peak wavelength. Our model predicted that we could achieve our goal of sub-picometer accuracy using gratings with as large as 80 % peak reflectance. We also verified this model experimentally using several different gratings with peak reflectances from 20 to 80 %.

Another important consideration is the grating's polarization-dependent wavelength shift (PDW), which can be described as a slight change in the center wavelength with polarization. PDW arises from intrinsic or strain-induced

asymmetries in the fiber core, asymmetry inherent to the grating side-writing process, or asymmetry due to the polarization of the UV writing beam. We have developed a method to determine a grating's PDW from measurements of the grating's reflectance at four orthogonal polarization states [4]. For wavelength references, we use only gratings with measured PDW much smaller than 1 pm.

2.2 Peak wavelength measurement

We used a polynomial curve fit routine to fit a fourth-order polynomial to the reflection spectra and then calculated the peak wavelength from the curve fit. We typically use the upper 30 % of the spectra in the curve fit, but one of our gratings has an unusually strong side lobe that could affect the curve fit, so for that grating we used the upper 20 %. This technique is relatively insensitive to noise and requires only a narrow, central portion of the grating's reflection spectrum. The dominant source of uncertainty in this method is the effect of noise on the reproducibility of the curve fit. To evaluate this uncertainty, we made repeated measurements of a single FBG's spectrum. We found that the curve-fit results changed by a maximum of 0.4 pm. Assuming a uniform probability density function with 0.4 pm extent, this corresponds to a standard uncertainty of 0.2 pm.

2.3 Stability of athermally-packaged gratings

It is well known that FBGs are very sensitive to both temperature and strain. To achieve our sub-picometer stability goal, we used athermally-packaged gratings. These gratings are mounted under slight strain between two materials with different coefficients of thermal expansion. The net effect is to approximately compensate for the intrinsic thermal expansion of the FBG. We measured the thermal response near room temperature of our athermally-packaged gratings and found that each was less than 0.5 pm/°C. This is insufficient to achieve our sub-picometer stability goals, so we included active temperature control with stability better than 0.02 °C.

The long-term stability of the athermal package is another important concern. Our measurements on several gratings from two different manufacturers show that the peak wavelengths tend to shift with time at rates as high as 7 pm/year. We tried various thermal cycles in an effort to accelerate the aging process and achieve better stability. We found that a thermal cycle from 0 to 80 °C, repeated 75 times, seems to improve the stability. In Fig. 1 we show the stability results for one of our gratings both before and after thermal cycling. For the four gratings that we exposed to thermal cycling, we measured post-cycling wavelength standard deviations of 0.2 to 0.5 pm over a period of 75 days.

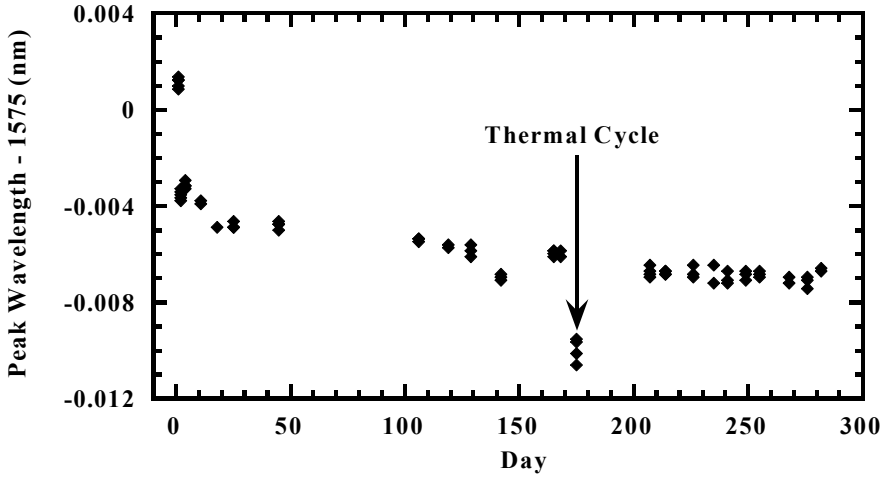

Figure 1. Peak wavelength stability of an FBG both before and after thermal cycling. We believe the measurements at day 175 may have been made before the grating's temperature reached equilibrium after thermal cycling.

3. Measurement systems

3.1 Tunable laser system

Our tunable laser measurement system is described in [2]. We use a wavelength meter that is periodically calibrated to a rubidium line to monitor the laser's wavelength. A tunable fiber Fabry-Perot filter removes much of the amplified spontaneous emission from the laser output, yielding a higher SNR. The SNR is further improved with a chopper and lock-in amplifiers at the detectors. We measure both the laser power and the power reflected by the FBG; we are then able to divide out laser power fluctuations. The uncertainty of this measurement is determined

primarily by the wavelength meter, with standard uncertainty less than 0.1 pm. This measurement, with its low uncertainty, is our primary method for characterizing the long-term stability of our gratings.

3.2 Optical spectrum analyzer (OSA)

Several of the participants in our FBG round robin used OSAs to perform their measurements [2]. Unfortunately, an OSA is often a poor choice if high-accuracy results are needed. One source of error is wavelength calibration. This error is often quite large, but it can be measured and corrected using a molecular absorption-line wavelength reference standard. However, after the wavelength calibration error is corrected, the OSA wavelength scale has a nonlinear wavelength uncertainty; we measured 2 pm nonlinearity over a very short wavelength range (2 nm), and some OSA specifications describe nonlinearities as large as ± 20 pm over a 40 nm wavelength range. Another source of error is the wavelength resolution of the OSA; its effect on the measured spectrum is to convolve the FBG spectrum with the OSA's instrument transfer function. If the wavelength resolution is comparable to the width of the FBG reflection spectrum, this convolution can significantly affect the measurement, particularly for the case of an FBG spectrum with strong asymmetry. The effect on our FBG measurements was as large as 3 pm for an OSA wavelength resolution of 70 pm. In theory, nonlinearity and wavelength resolution effects could be measured and corrected, but in practice it is difficult to measure these effects accurately. Therefore, an OSA is not appropriate for high-accuracy (<10 pm) measurements.

3.3 Interferometric measurement

We also measured our set of four athermally-packaged gratings using an interferometric system as described in [5]. From a measured 2^{16} point interferogram of the FBG's reflected light, we calculated the centroid wavelength of each grating using a Hilbert transform of the interference signal. The Hilbert transform yields an analytic signal, with the phase of the analytic signal determined by the grating's centroid wavelength over the 2-nm spectral window used in the Hilbert transform. Performing a linear curve fit to the central portion of the phase of the analytic signal gives the centroid wavelength of the FBG. In Table 1 we show a comparison of the interferometric measurement results (average of 10 measurements) with the centroid and peak wavelengths calculated from a 2-nm wide tunable laser measurement of the same gratings.

Table 1. Comparison of FBG wavelengths measured by tunable laser (TL) and interferometric (I) systems. The numbers in parenthesis represent the uncertainty in the last digit of each measurement.

Grating	TL (peak) (nm)	TL (centroid) (nm)	I (centroid) (nm)	Δ (peak - centroid) (pm)	Δ (TL-I) (pm)
A	1534.9734 (5)	1534.9790	1534.9788 (4)	-5.6	0.2
B	1547.4853 (2)	1547.4859	1547.4861 (4)	-0.6	-0.2
C	1559.9882 (2)	1559.9820	1559.9826 (7)	6.2	-0.6
D	1574.9930 (2)	1574.9867	1574.9877 (10)	-3.7	-1.0

4. Conclusions

A key problem in the use of FBGs as wavelength references is the possibility that the wavelengths may change with time as a result of factors such as the relaxation of stress in the athermal packages. A passive wavelength reference based on FBGs may require periodic calibration at intervals as frequent as 6 – 12 months. High-accuracy measurements, such as the tunable laser or interferometric measurements described above, are required to calibrate the device. It is important to note that some measurements return the peak wavelength, and others yield the centroid wavelength; for gratings with asymmetric reflection spectra, the peak and centroid wavelengths can differ by as much as 6 pm.

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